

Model uncertainties on limits for quantum black hole production in dijet events from ATLAS

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Abstract

We study the model uncertainties on limits for quantum black hole production in dijet events from ATLAS. For models that assume a hard-disk cross section, the model uncertainty on the threshold mass limits is about 5%. If the trapped surface calculation is used for the cross section, the ATLAS mass threshold limits are below 2 TeV for all number of dimensions. Using the ATLAS data in the context of the Randall-Sundrum type-1 model gives a threshold mass lower limit of 2.84 TeV.

1 Introduction

The ATLAS experiment has set limits on quantum black hole production and decay to dijets [1]. The analysis has recently been updated to 4.8 fb⁻¹ of 7 TeV data [2]. The main result of the new analysis is reproduced in Fig. 1. ATLAS gives the results as a function of the fundamental higher-dimensional Planck scale¹ M_D . The model used by ATLAS equates the value of the Planck scale with the turn-on, or energy threshold, for quantum black hole production. A more model independent interpretation would be to call the M_D -axis in Fig. 1 the mass threshold for quantum black hole production. We use this terminology throughout this note.

Several similar models have been proposed to describe the behaviour of quantum black holes [3, 4, 5]. We study the sensitivity of the ATLAS results to the different models. The ATLAS results are based on the BlackMax Monte Carlo (MC) event generator [6]. To enable the calculation of difference models we use the QBH MC event generator [7]².

¹ATLAS refers to this Planck scale as the “reduced” Planck scale, which is usual reserved for the four-dimensional Planck scale $\bar{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$.

²The use of QBH here refers to the MC event generator. In the ATLAS studies QBH it refers to “Quantum Black Hole”.

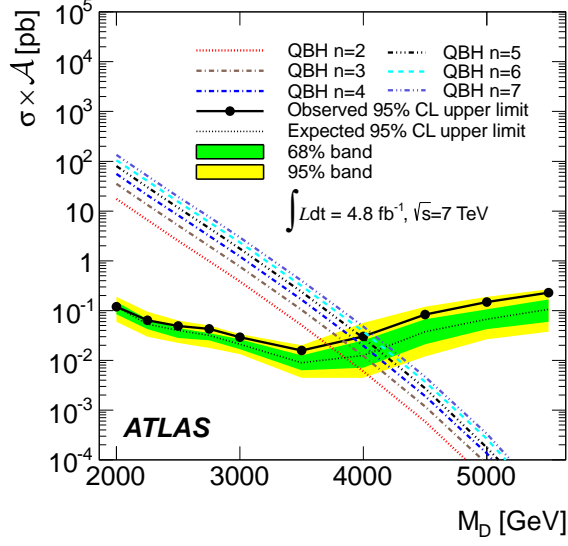


Figure 1: The 95% C.L. upper limits on $\sigma \times \mathcal{A}$ as function of the reduced Planck mass M_D of the quantum black hole models using $F_\chi(m_{jj})$ (black filled circles). The black dotted curve shows the 95% C.L. upper limit expected from Monte Carlo and the light and dark yellow shaded bands represent the 68% and 95% contours of the expected limit, respectively. Theoretical predictions of $\sigma \times \mathcal{A}$ are shown for various numbers of extra dimensions. From Ref. [2].

2 Two-body Branching Ratio

Different models for the decay of a quantum black hole to two partons could give different results for the mass threshold. Prior to version 2.00.2 of BLACKMAX there was an error in the two-body branching ratio calculation. The erroneous formula is still in the manual [8] as Eq. (23) of that document. In this equation, the prefactor should not be raised to an exponent. This formula also appears in error in the original Meede and Randell paper [3] from which BLACKMAX is based on. Published results from ATLAS use a version of BLACKMAX with the corrected formula.

Models for the number of particles produced from the decay of a quantum black hole use a Poisson distribution

$$p(n; \nu) = \frac{\nu^n e^{-\nu}}{n!}, \quad (1)$$

where n is the number observed and ν is the mean of that distribution, to describe the probability of different number of final state particles. Different models use this formula in different ways to predict the probability of a two-body decay.

In BLACKMAX, the two-body branching ratio is given by

$$BR = p(0; \nu) + p(1; \nu) + p(2; \nu). \quad (2)$$

The interpretation is that $p(0; \nu)$ and $p(1; \nu)$ represent processes in which the black hole does not form, and thus the two incident partons become the outgoing partons. Both these terms thus represent a gravitational scattering process using the classical hard-disk cross section. The $p(2; \nu)$ term represents a proper two-body decay of a shortlived quantum black hole. It is implied by using Eq. (2) that all two-body final states consist of two partons, with no leptons, or gauge bosons allowed. Using Eq. (2) for the two-body branching ratio reduces the limits on the threshold mass by at most 30 GeV from the case of not including a branching ratio.

In QBH, the two-body branching ratio is given by

$$BR = p(1; \nu) / (1 - p(0; \nu)) . \quad (3)$$

The interpretation is that we are interested in true decays, not scattering processes with the classical hard-disk cross section. Thus $p(0; \nu)$ and $p(1; \nu)$ do not represent physical production or decays states, and hence are removed from the calculation and the Poisson distribution is renormalised. $p(1; \nu)$ represents a proper two-body decay in which one particle is emitted from the black hole and the remaining black holes state becomes the second particle. This is also the interpretation used by the MC event generator Charybdis2 [9]. Using Eq. (3) for the two-body branching ratio reduces the limits on the threshold mass by at most 120 GeV from the case of not including a branching ratio, or at most 90 GeV relative to BLACKMAX.

Not all two-body final states should be considered to give rise to two jets. Based on Hawking emissivities in higher dimensions and enumerating the number of degrees of freedom of the Standard Model, the probability of the two final states being both partons is about 64% [5]. This lowers the limits on the threshold mass by a further 90 GeV. Thus the QBH model gives results at least 180 GeV lower than the ATLAS results.

The results of the different models for the branching ratio are shown in Fig. 2. The BLACKMAX curve corresponds to the model used by the ATLAS experiment. The alternative interpretations are shown as the QBH curves. The $\sigma(\text{total})$ curve presents the case of no two-body branching ratio. It assumes a black hole is always formed and always decays to two partons which form two jets. The two-body case implements the two-body branching ratio in Eq. (3). Since not all decay particles from black holes are partons leading to jets, the dijet curve shows the results when allowing for non-jet final states. BLACKMAX and the ATLAS analysis fail to take into consideration the case where not all the final state particles appear as jets in the detector.

Table 1 shows the resulting lower mass limits for the different model assumptions.

3 Cross Section Uncertainties

Other different model assumptions, beside those of branching ratio, lead to different cross sections and hence different limits on the threshold mass. These are not restricted to models of quantum black holes but also apply to the classical black hole models. The scale used in the parton distribution functions can lead to cross section differences. BLACKMAX uses the mass of the black hole, while QBH also allows the inverse of the gravitational radius $1/r_g$ to

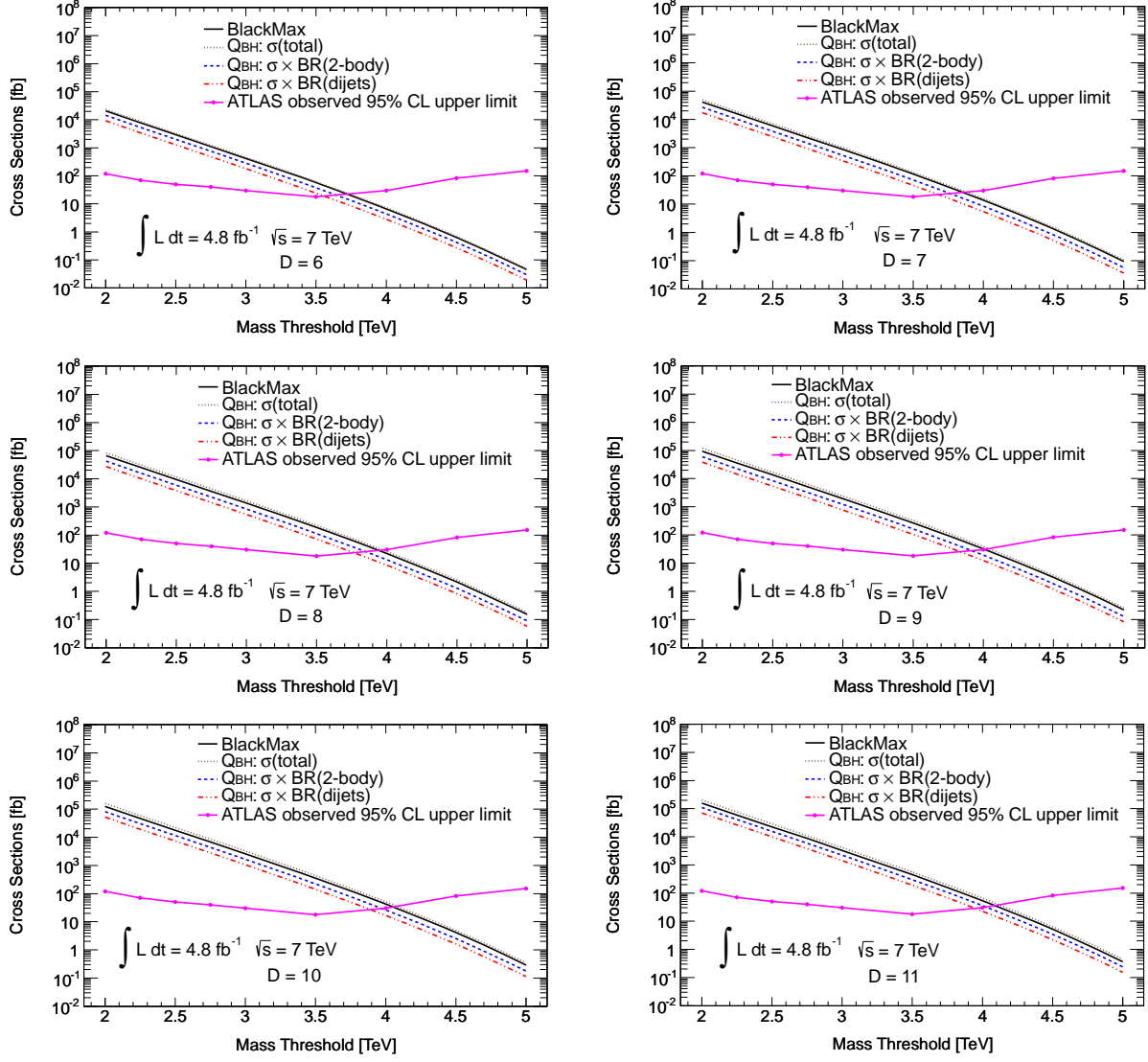


Figure 2: Cross section versus mass threshold for different total number of dimensions D and branching ratio models.

D	BLACKMAX [TeV]	QBH [TeV]		
		$\sigma(\text{total})$	BR(2-body)	BR(dijets)
6	3.71	3.73 (+0.02)	3.64 (-0.07)	3.56 (-0.15)
7	3.84	3.88 (+0.04)	3.76 (-0.08)	3.67 (-0.17)
8	3.92	3.97 (+0.05)	3.85 (-0.07)	3.76 (-0.16)
9	3.99	4.03 (+0.04)	3.91 (-0.08)	3.83 (-0.16)
10	4.03	4.07 (+0.04)	3.98 (-0.05)	3.89 (-0.14)
11	4.07	4.11 (+0.04)	4.02 (-0.05)	3.95 (-0.12)

Table 1: Lower limits at 95% C.L. on the threshold mass versus total number of dimensions D for different quantum black hole branching ratio models. The numbers in brackets are differences relative to BLACKMAX.

D	BLACKMAX [TeV]	QBH [TeV]	
		QCD scale = $1/r_g$	Form Factor
6	3.71	3.73 (+0.02)	3.88 (+0.17)
7	3.84	3.90 (+0.06)	4.04 (+0.20)
8	3.92	4.01 (+0.09)	4.12 (+0.20)
9	3.99	4.07 (+0.08)	4.18 (+0.19)
10	4.03	4.11 (+0.08)	4.24 (+0.21)
11	4.07	4.15 (+0.08)	4.28 (+0.19)

Table 2: Lower limits at 95% C.L. on the threshold mass versus total number of dimensions D for different quantum black hole cross section models. The numbers in brackets are differences relative to BLACKMAX.

be used. Using the inverse gravitational radius can raise the limit on the threshold mass by as much as 70 GeV. Of course, different choices for the partons distribution functions can give significant differences in cross section. We do not consider these differences here but see Ref. [5] for some examples.

One can include a form factor based on the trapped surface calculation that is also used for classical black holes. Including form factors raise the mass thresholds by as much as 200 GeV.

The results of these two model assumptions are shown in Fig. 3, and Table 2 shows the resulting lower mass limits for the different model assumptions.

3.1 Additional Limits

It is possible to obtain additional information from the ATLAS data. So far, ATLAS has considered only ADD-type models. It is also possible to interpret the ATLAS data in terms of the Randall-Sundrum type-1 model. The result is shown in Fig. 4 and the mass threshold is restricted to be above 2.84 TeV.

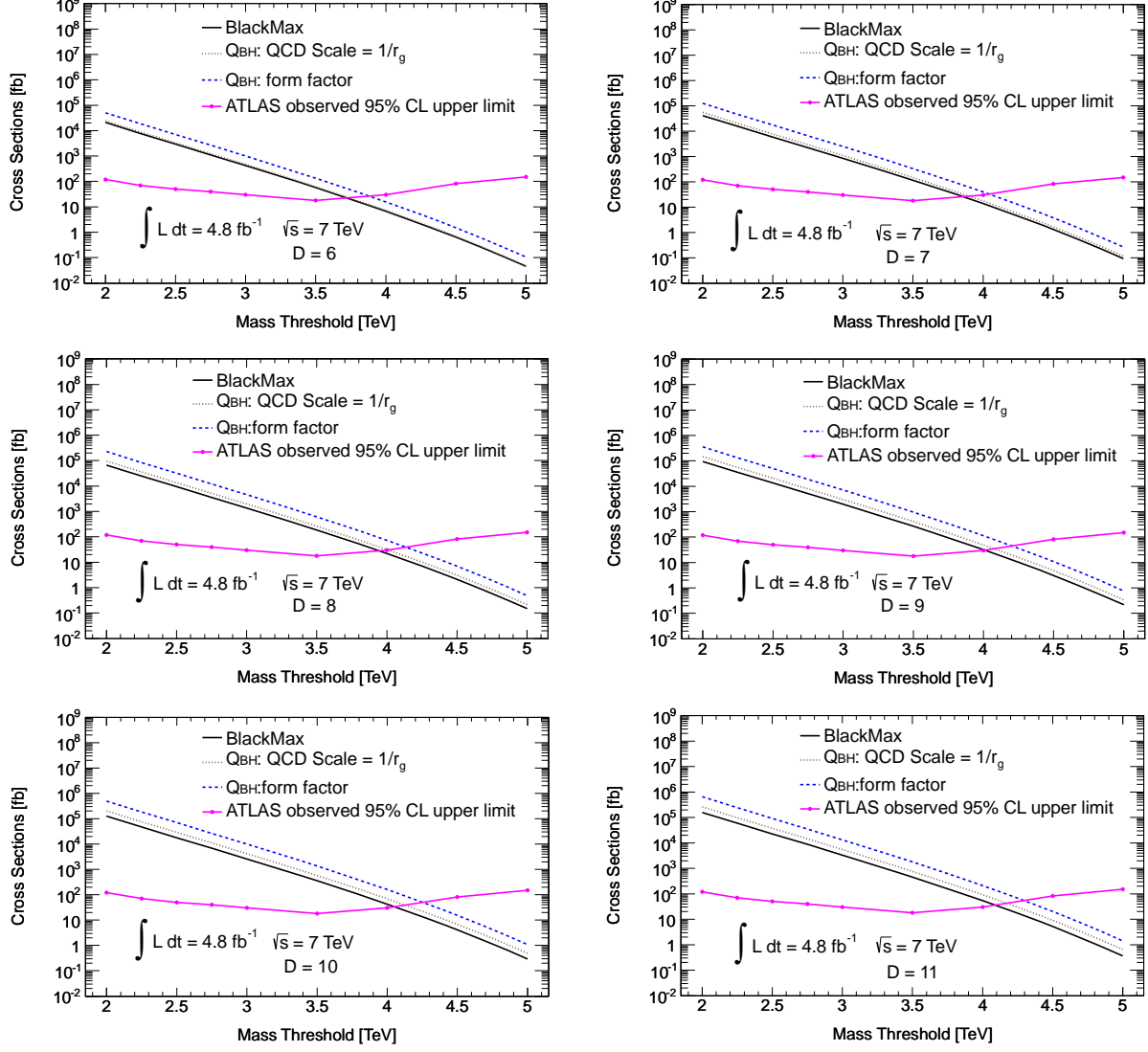


Figure 3: Cross section versus mass threshold for different total number of dimensions D and for different cross section models.

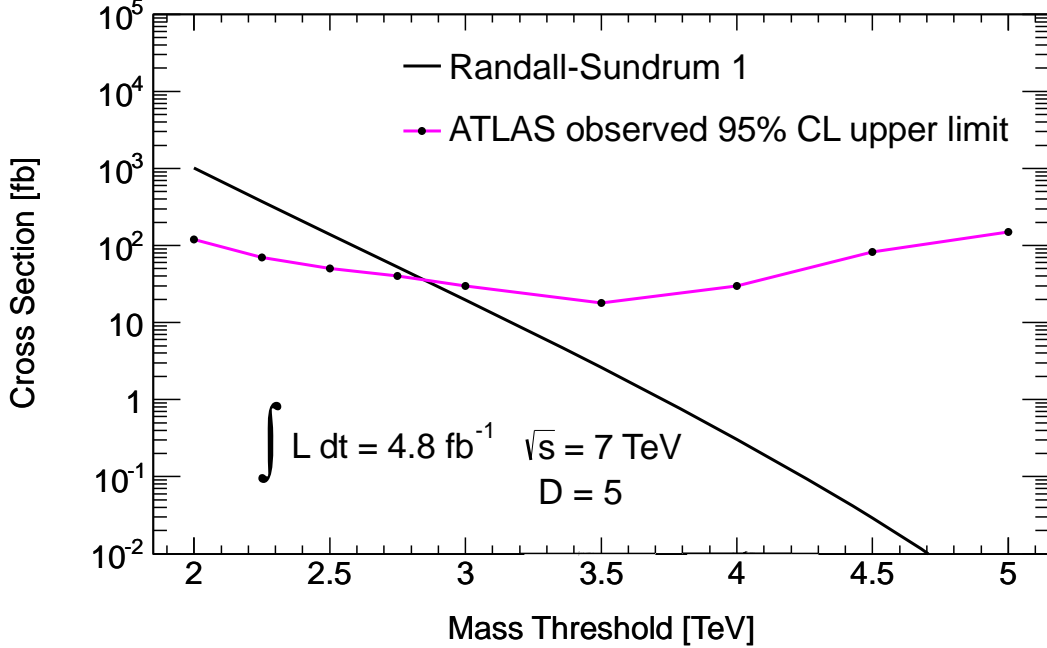


Figure 4: Randall-Sundrum type-1 model cross section versus mass threshold.

The most significant effect on the cross section is the amount of energy that goes into the formation of the black hole. The classical cross section represents an upper bound, while the trapped surface calculation gives a lower bound. Figure 5 show the effect of using the trapped surface calculation. For this case, the ATLAS lower limits on the mass threshold are all below 2 TeV.

4 Decay Uncertainties

Different models for the decay have no effect on the cross section, other than the branching ratio, but may effect the experimental acceptance. Differences due to final state particle types in the branching ratio have already been discussed. ATLAS assumes an acceptance of 100% when calculating the threshold mass limits. We believe the difference in acceptance due to different models for the decay are negligible.

It is thus unnecessary to preform a full detector simulation for all the models and only the relative normalization between the different models is important. The $F_\chi(m_{jj})$ distribution observed by ATLAS in setting the limits would also be little changed from one model to another.

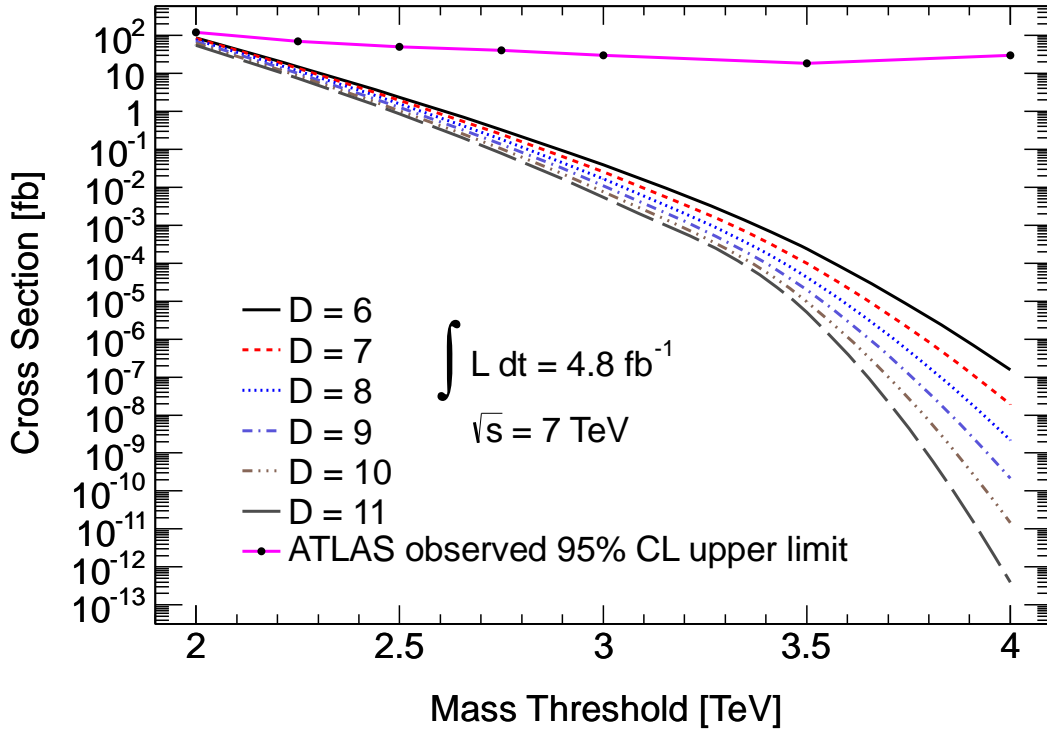


Figure 5: Trapped surface cross section versus mass threshold.

5 Conclusions

Different model assumptions for the cross section raise the limits on the mass threshold by at most 210 GeV. Different treatments of the branching ratio reduce the limits on the mass threshold by at most 170 GeV. Thus, for models that assume a hard-disk cross section, we may assign an approximate systematic error due to model dependence of about 5% on the ATLAS results.

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